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(71) Applicant: THE BABCOCK & WILCOX COMPANY
1010 Common Street P.O. Box 60035
New Orleans Louisiana 70160(US)

(72) Inventor: Kaya, Azmi
2365 Woodpark Road
Akron Ohio 44313(US)

(72) Inventor: Keyes, Marion Alvah
120 Riverstone Drive
Chagrin Falls Ohio 44022(US)

(74) Representative: Cotter, Ivan John et al,
D. YOUNG & CO. 10 Staple Inn
London WC1V 7RD(GB)

(54) Heat exchanger performance monitors.

(57) A performance monitor (20) generates a fouling factor (FF) which indicates the level of fouling of a heat exchanger (10) having a heat exchange surface area and through which passes a heat exchange medium having a known specific heat. Temperature transmitters (TT_1, TT_2, TT_3) are utilised to obtain values for the input and output temperatures of the heat exchange medium as well as the temperature in the heat exchanger of a heat exchange fluid used to transfer heat to or from the heat exchange medium. Modules (30, 40, 50, 60) are used to generate values for an actual heat transfer coefficient (U_{act}) and a nominal heat transfer coefficient (U_{ava}) in the heat exchanger (10) as a function of the temperatures, flow rate and constant parameters such as area and specific heat, for the heat exchanger (10). The actual heat transfer coefficient (U_{act}) is compared with the nominal or original heat transfer coefficient (U_{ava}) to determine if there is any deterioration in the coefficients which reflects fouling of the heat exchanger. A simple ratio of the nominal to actual heat transfer coefficients is taken (61) as a measure of the fouling factor (FF).

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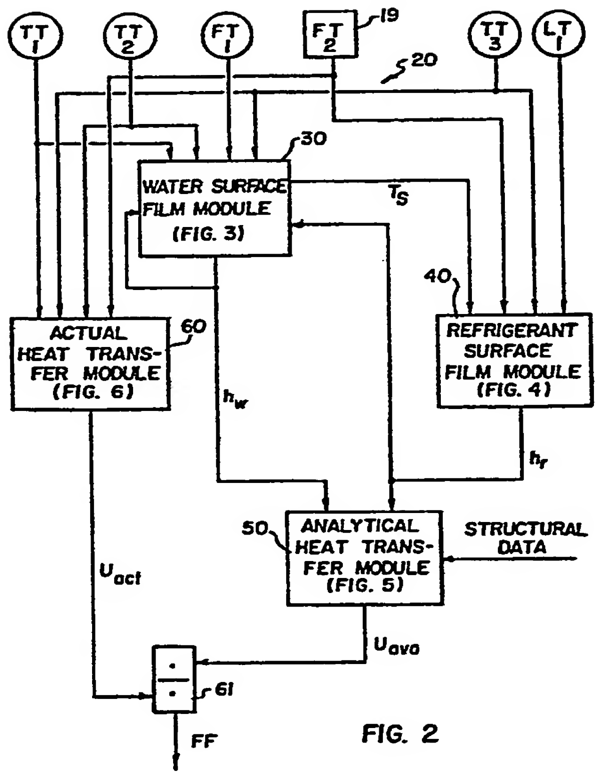

TT 1
TT 2
FT 1
FT 2
19
TT 3
LT 1
20
30
WATER SURFACE FILM MODULE (FIG. 3)
T_S
40
REFRIGERANT SURFACE FILM MODULE (FIG. 4)
ACTUAL HEAT TRANS- FER MODULE (FIG. 6)
60
h_w
h_r
50
ANALYTICAL HEAT TRANS- FER MODULE (FIG. 5)
STRUCTURAL DATA
U_{act}
U_{avo}
61
FF

FIG. 2

HEAT EXCHANGER PERFORMANCE MONITORS

This invention relates to heat exchanger performance monitors. More specifically, the invention relates to a performance monitor for generating a fouling factor of a heat exchanger.

The performance of heat exchangers can be monitored. Such monitoring, however, requires extensive calculations which, hitherto, have been done using computers and high level programming languages. Such performance calculations have been disclosed in "Trouble-Shooting Compression Refrigeration Systems" by K. J. Vargas, Chem. Engineering, 22 March 1982.

In order to determine the performance capacity of a heat exchanger under various operating conditions, deviations of the heat exchanger from design conditions must be accounted for by these extended calculations.

Experimental data has also been used to determine heat exchanger performance, as described in "Controlling Chiller Tube Fouling" by G. Leitner, ASHRAE Journal, Feb. 1980. Such experimental data is not, however, always available.

Currently, computers are employed to determine the performance of heat exchangers in a prompt manner. The continuous availability of performance measurements helps in diagnosing several problems as they occur. However, computers require high level language and highly trained personnel. This results in high costs for monitoring the heat exchangers.

According to one aspect of the present invention there is provided a performance monitor for generating a fouling factor of a heat exchanger having a heat exchange surface area against one side of which a heat exchange medium passes, the medium having a specific heat value, the performance monitor comprising:

first temperature transmitter means for supplying a signal corresponding to an output temperature of heat exchange medium from the heat exchanger;

second temperature transmitter means for supplying a signal corresponding to an input temperature of medium to the heat exchanger;

third temperature transmitter means for supplying a signal corresponding to a temperature of the heat exchanger on an opposite side of the heat exchange surface area;

mass flow rate means for supplying a signal corresponding to a mass flow rate of medium through the heat exchanger;

an actual heat transfer module connected to the first, second and third temperature transmitter means and to the mass flow rate means for calculating an actual heat transfer coefficient as a function of the input, output and heat exchanger temperatures, the mass flow rate, specific heat value and surface area;

nominal heat transfer co-efficient means for supplying a signal corresponding to a nominal heat transfer coefficient; and

a divider unit connected to the actual heat transfer module and the nominal heat transfer coefficient means for obtaining a ratio of the nominal to actual heat transfer coefficients which corresponds to the fouling factor.

According to another aspect of the present invention there is provided a heat exchanger performance monitor which utilises a plurality of modules each including simple calculating units for obtaining a calculated value for an actual heat transfer coefficient and also a theoretical value for the nominal or original heat transfer coefficient value.

A preferred embodiment of the present invention described in detail hereinbelow provides a monitoring system or monitor which has equivalent performance to prior art computer monitoring systems while costing less and being faster in operation. Essentially, the advantages of an analog device as well as a computer are combined in the preferred monitor embodying the invention.

The preferred monitor comprises a plurality of individual function blocks which are structured and assembled to perform the same operations as a high cost computer.

The preferred heat exchanger performance monitor is simple in design, rugged in construction and economical to manufacture.

The invention is applicable to heat exchangers such as pre-coolers, air coolers, evaporators and condensers, and also to other devices having heat transfer surfaces such as boilers, for the purpose of determining fouling and slagging. The term "heat exchanger" is therefore to be construed broadly. A monitoring system or monitor embodying the invention can be

used, for example, to determine when a soot blowing operation should be commenced in a boiler.

The invention will now be further described, by way of illustrative and non-limiting example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic block diagram showing an evaporator as an example of a heat exchanger in combination with a performance monitor embodying the present invention;

Figure 2 is a block diagram showing fouling factor monitoring logic of the performance monitor for generating a signal corresponding to a fouling factor of the heat exchanger;

Figure 3 is a block diagram showing a water surface film module used in the circuit of Figure 2;

Figure 4 is a block diagram showing a refrigerant surface film module used in the circuit of Figure 2;

Figure 5 is a block diagram of an analytical heat transfer module used in the circuit of Figure 2; and

Figure 6 is a block diagram of an actual heat transfer module used in the circuit of Figure 2.

The drawings illustrate one embodiment of performance monitor which is particularly useful in monitoring the extent of fouling in a heat exchanger and, in particular, an evaporator.

As noted above, one of the reasons for degraded performance of a heat exchanger is fouling. There are other reasons, such as lack of flow, which may reduce the heat transfer capability. The present monitor, however, isolates the effects of velocity to single out fouling as the cause of degraded heat transfer. The Heat Transfer equation is:

$$q = U.A.Tm \qquad (1),$$

where:

q = heat flow (W or Btu/h),

U = overall heat transfer coefficient ($W/m^2.K$ or $Btu/h.ft^2.^\circ F$),

A = surface area (m^2 or ft^2), and

Tm = logarithmic mean temperature difference.

The measured (actual) value of U_{act} is compared with its normal value to determine the extent of fouling. The actual value is found from measurements as:

$$U_{act} = q/(A.Tm) \qquad (2)$$

Each value on the right hand side of Equation (2) is measured or known.

In general, two different fluids (such as water and refrigerant) exchange heat. The change in mean temperature, ΔT_m, is written as a function of T_{hot} = medium input, T_{cold} = medium output, T'_{cold} = refrigerant (or heat transfer fluid) input and T'_{hot} = refrigerant output.

The function is:

$$T_m = \frac{(T_{hot} - T'_{cold}) - (T_{cold} - T'_{hot})}{\ln(\frac{T_{hot} - T'_{cold}}{T_{cold} - T'_{hot}})} \qquad (3)$$

As shown in Figure 1, T refers to chilled water temperature and T' to refrigerant or fluid temperature where the heat exchanger is an evaporator and where water is the medium. T' may be constant and Equation (3) still applies. The value of q can be measured as the heat picked up by the water. The q value is found from measurements of T_{cold}, T_{hot} and mass flow rate M_w as:

$$q = C_p M_w (T_{hot} - T_{cold})$$

where C_p = the specific heat of water, which is known. The area of the heat exchanger is known as well.

The actual value of the heat exchanger coefficient (U_{act}) is found from the measurements by combining Equations (2) and (4). The original or nominal value (U_{ava}) of the heat transfer coeffieicnt is found by calculating a given fluid velocity and temperature conditions. ASHRAE Guide Books give the relation for calculating U values. For an evaporator with chilled water inside the tubes, U is given by:

$$U = \frac{1}{\frac{1}{\phi_r h_r} + \frac{X}{K}\frac{A_o}{A_m} + \frac{A_o}{A_i}(\frac{1}{h_w} + r_f)} \qquad (5)$$

where:

ϕ_r = fin shape factor,

h_w, h_r = film coefficients for water and refrigerant,

X = wall thickness,

K = thermal conductivity of the tube material,

A_m = mean area,

A_o, A_i = outside and inside areas, and

r_f = fouling factor.

In case U_{ava} is provided by the manufacture of the evaporator, Equation (5) should be checked against the manufacturer's value and should be corrected by a multiplication factor K_f if needed.

The values of h_r, h_w are velocity and temperature dependent and the K value may be temperature dependent. Therefore, these values should be calculated, and U should be updated in order to compare it with the experimental data.

A general formula for the h (film coefficient) value is given by:

$$h = C\frac{K}{d}\left(\frac{Md}{\mu}\right)^n\left(\frac{\mu C_p}{K}\right)^m \qquad (6)$$

where:

d = tube diameter,

M = mass velocity ((g/s.m^2) or lb/(s.ft^2)),

μ = viscosity, and

m,n,C = constants.

The values of m, n, C depend upon the application or type of heat exchanger. Although the form of Equation (6) may differ in special cases such as viscous fluids, the same terms are used.

In the following development of U, h_w and h_r are tested as general non-linear functions of temperature and velocity. The corrections on nominal values of h_r^o and h_w^o, due to the variations of the temperature and the velocity, are made.

The case of an evaporator monitor, as illustrated in Figures 1 to 6, will now be treated. The monitor is applied to a flooded evaporator 10 with water inside tubes shown schematically at 12. The refrigerant velocity will be small as compared with other types of evaporators. However, mass velocity of refrigerant can be taken from measurements of compressor inlet flow at an inlet 16 of a compressor 14 or it can directly be measured from an outlet 17 of a condensor 18. Here, the compressor measurements at its inlet 16 are utilised.

The evaporator system used with the evaporator monitor is shown in Figure 1. Fouling monitor logic 20 is shown in Figure 2 and includes four modules, namely a water surface film module 30, a refrigerant surface film module 40, an analytical heat transfer module 50, and an actual heat transfer module 60. Note that the values h_w and h_r are fed back into the water surface film module 30 (detailed in Figure 3) to calculate the surface temperature Ts of the tubes. Similarly, the refrigerant surface film module 40 of Figure 2 is shown in detail in Figure 4. The values h_w and h_r are fed into the analytical heat transfer module 50 (shown in detail in Figure 5) along with structural data to calculate the available value of heat transfer coefficient, U_{ava}, as in Equation (5). The actual value of heat transfer coefficient, U_{act}, is determined in the actual heat transfer module or unit 60 shown in detail in Figure 6. Going back to Figure 2, the fouling factor, FF, is determined as the ratio of actual and original values of U. Namely,

$$FF = \frac{U_{ava}}{U_{act}} \qquad (7)$$

The value of FF gives an indication of the cleanliness of the heat transfer surfaces independently of the other variables.

This fouling monitor logic 20 is general and applies to other exchangers. The structures of Figures 3 and 4 determine h_w and h_r from Equation (6), respectively. In Figures 3 and 4, any of the optional modules can be energised to eliminate the effect of a particular variable by setting $K_1 = 1$ and $K_2 = 0$. Otherwise, the values are set at $K_1 = 0$ and $K_2 = 1$ to include the effect. The functions "f" in Figures 3 and 4 are generated by varying a particular variable in Equation (6). The method of generating the functions "f" is given below. The relationship for h_w and h_r in several heat exchanger applications are given in the ASHRAE Guide Books.

Consider h_w, given in Equation (6) a non-linear function of temperature and mass flow:

$$h_w = G(T_w, M_w, T_s) \qquad (8)$$

where at nominal conditions the expression

$$h_w^o = G(T_w^o, M_w^o, T_s^o) \qquad (9)$$

holds. Writing:

$$h_w = h_w^o \frac{h_w}{h_w^o} \tag{10}$$

where:

$$\frac{h_w}{h_w^o} = \underbrace{\left[\frac{(h_w)^{T_w}}{h_w^o}\right]}_{f_1(T_w)} \underbrace{\left[\frac{(h_w)^{M_w}}{h_w^o}\right]}_{f_2(M_w)} \underbrace{\left[\frac{(h_w)^{T_s}}{h_w^o}\right]}_{f_3(T_s)} \tag{11}$$

The value of the numerator $f_1(T_w)$ is determined from Equation (6) by calculating h_w for various T_w values while the other variables are held at their nominal values M_w^o and T_s^o. The functions "f" are used in Figures 3 and 4.

Water cooled condensers and precoolers can also be monitored in the same way as the evaporator by the monitor embodying the invention. The heat transfer q can either be calculated by measuring condenser water parameters and using Equation (4) or using the refrigerant side measurements. In that case the q value for a condenser is written as:

$$q = M_r \ (h_{gas} - h_{liq}) \tag{12}$$

where:

m_r = refrigerant mass flow rate (g/h or lb/h),
h_{gas} = enthalpy of refrigerant entering, and
h_{liq} = enthalpy of refrigerant leaving.

For evaporative and air-cooled condensers it is better to use Equation (12) for q. For air-cooled condensers, water is replaced by air and the same equations apply. ΔT_m is calculated similarly.

For evaporative condensers, there is an intermediate fluid water between refrigerant and air. Determining U_{act} is identical to the other cases. The average value of ΔT_m for refrigerant to water and ΔT_m for refrigerant to air is used as ΔT_m.

For the analytical heat transfer coefficient, three surface film coefficients have to be calculated. Their calculations are covered in Equation (6). A modified relation over Equation (5) is:

$$U = \frac{1}{\frac{1}{\phi_r h_r} + \frac{X}{K}\frac{A_o}{A_m} + \frac{A_o}{A_i}\left(\frac{1}{h_w} + \frac{1}{h_a} + r_f\right)} \qquad (13)$$

where:

h_a = film coefficient for air.

To avoid undue complication, manufacturer's data should be used if possible. The functional relations as in Equation (10) can be developed from the manufacturer's data in case the analytical calculations become impractical.

In greater detail, as shown in Figure 1, three temperature transmitters TT_1, TT_2 and TT_3 are associated with the evaporator 10. The temperature transmitter TT_1 measures the output temperature of the medium, in this case cold water, which has a temperature T_{cold}. The transmitter TT_2 measures the input temperature T_{hot} of the water. The temperature transmitter TT_3 is used to measure the mean temperature in the evaporator 10. A single temperature value is used therefore for refrigerant input and output temperature in Equation (3). Added accuracy can be obtained by using different temperature transmitters for the input and output temperature of the refrigerant or other heat exchange fluid in another heat exchanger environment.

The flow FT_2 of refrigerant through the evaporator 10 is obtained from a mass flow logic unit 19 at the inlet 16 of the compressor 14 which is of known structure. The signal from FT_2 is applied to the fouling monitor logic 20.

The level of refrigerant in the evaporator 10 is measured by a level transmitter LT_1. This value is used in obtaining the original or nominal heat transfer coefficient value in the circuitry of Figure 4.

The mass flow rate of heat exchange medium is measured by a flow transmitter FT_1.

The refrigerant is supplied through the evaporator 10 by the compressor 14 in the refrigerant circuit. Controllable valves are shown, which are of known structure.

The refrigerant is supplied through the condenser 18 which is also cooled by a cooling unit 11, also of known design.

Figure 2 shows the fouling monitor logic 20 which forms the performance monitor embodying the invention.

The actual heat transfer module 60 is connected to the temperature transmitters TT_1, TT_2 and TT_3, as well as the mass flow logic unit 19. As shown in greater detail in Figure 6, the module 60 generates a value corresponding to the actual heat transfer coefficient U_{act}.

The original or nominal heat transfer coefficient U_{ava} can be used as a known value or can be ascertained using the three modules 30, 40 and 50 shown in Figure 2 and detailed in Figures 3, 4 and 5, respectively.

The nominal or original heat transfer coefficient U_{ava} is divided by the actual value, U_{act}, in a first divider unit 61 to generate the fouling factor FF as described in Equation (7).

Figure 3 shows the water surface film module 30 which uses simple functional units such as summing units 32, multiplication units 34 and a second dividing unit 36, as well as additional somewhat more complicated units, to generate the values h_w and T_s from Equation (6) by the use of Equation (6) and Equations (8) to (11). Optical modules 38 can be used to eliminate the effects of T_w, M_w and T_s.

Function generators 31 are utilised to generate more complex functions, but are also of modular design. These function generators ar utilised to generate the functions needed in Equation (11).

Figure 4 illustrates the refrigerant surface film module 40 for calculating h_r. Here again, function generators 41 are utilised for generating the various functions needed for example in Equation (11), as well as multipliers 44 and summing units 42. Optional modules 43, which are similar to the modules 38 of Figure 3, are also provided.

Figure 5 illustrates the analytical heat transfer module 50 which is connected to the water surface film module 30 and refrigerant surface film module 40, and is also made up of simple functional units such as summing units 52, a multiplier 54 and a divider unit 56. The module 50 implements Equation (5) to calculate the nominal or original heat transfer coefficient U_{ava} as a function of h_w and h_r, supplied from the units 30 and 40, respectively. The structural data as described in Equation (5) is also utilised.

Figure 6 illustrates the actual heat transfer module 60 which is used to run through Equations (2), (3), and (4) for calculating the actual heat transfer coefficient U_{act}. Difference units 63 obtain the various differences between the temperatures as supplied by the temperature transmitters TT_1, TT_2 and TT_3. A mass flow meter 67 (of known structure) supplies the mass

flow rate M_w to a multiplier 64, the output of which is multiplied, in a multiplier 65 by the ratio of the specific heat for the medium (in this case water) and the surface area of the heat exchange surface. A divider 66 is used in conjunction with the difference units to obtain the ratio whose natural logarithm ln is taken in a function unit 61. Further dividers 66 are used to generate ultimately the U_{act} value.

It is noted that the various modules and compartmentalised function and simple mathematic operational blocks can all be provided by a NETWORK 90 instrument. NETWORK 90 is a trademark of the Bailey Controls Company of McDermott Incorporated. The use of such a modular arrangement avoids the use of a computer with its associated high level programming language to achieve the same purpose. The monitoring purpose is also achieved more rapidly.

CLAIMS

1. A performance monitor for generating a fouling factor of a heat exchanger having a heat exchange surface area against one side of which a heat exchange medium passes, the medium having a specific heat value, the performance monitor comprising:
first temperature transmitter means (TT_1) for supplying a signal corresponding to an output temperature (T_{cold}) of heat exchange medium from the heat exchanger (10);
second temperature transmitter means (TT_2) for supplying a signal corresponding to an input temperature (T_{hot}) of medium to the heat exchanger (10);
third temperature transmitter means (TT_3) for supplying a signal corresponding to a temperature of the heat exchanger (10) on an opposite side of the heat exchange surface area;
mass flow rate means for supplying a signal corresponding to a mass flow rate of medium through the heat exchanger (10);
an actual heat transfer module (60) connected to the first, second and third temperature transmitter means (TT_1, TT_2, TT_3) and to the mass flow rate means for calculating an actual heat transfer coefficient (U_{act}) as a function of the input, output and heat exchanger temperatures, the mass flow rate, specific heat value and surface area;
nominal heat transfer co-efficient means for supplying a signal corresponding to a nominal heat transfer coefficient (U_{ava}); and
a divider unit (61) connected to the actual heat transfer module (60) and the nominal heat transfer coefficient means for obtaining a ratio of the nominal to actual heat transfer coefficients which corresponds to the fouling factor (FF).

2. A performance monitor according to claim 1, wherein the nominal heat transfer coefficient means comprises a heat exchange medium surface film module (30) for calculating a film coefficient of the heat exchange medium as a function of the input and output temperatures of the medium and a flow rate of the medium through the heat exchanger (10), the heat exchanger including a heat exchange fluid passing therethrough on the

opposite side of the heat exchange surface area, a fluid surface film module (40) for calculating a film coefficient for the fluid as a function of the mass flow rate, the heat exchanger temperature and a flow rate of fluid through the heat exchanger, and an analytical heat transfer module (50) for calculating the nominal heat transfer coefficient as a function of the medium and fluid film coefficients.

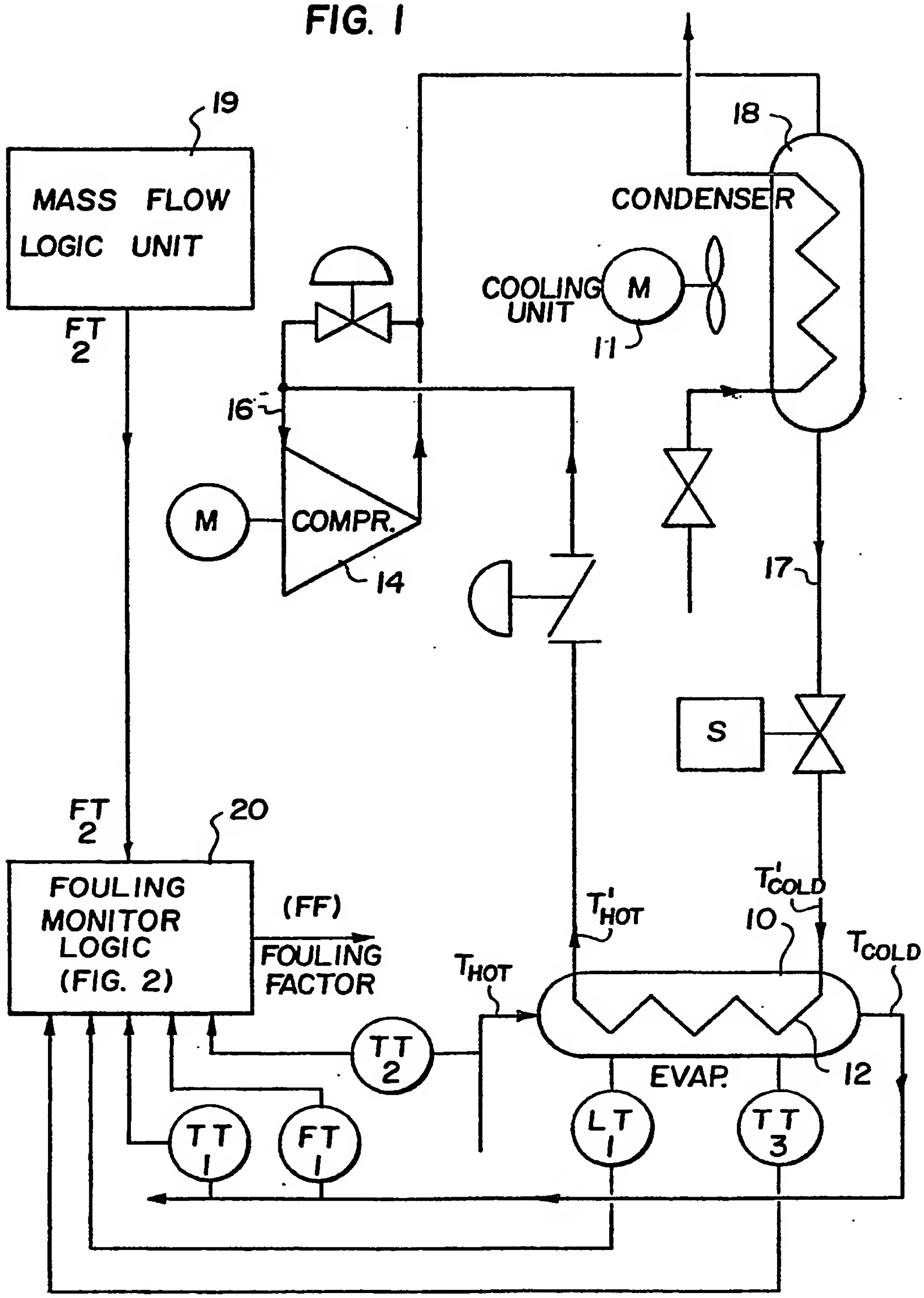
3. A performance monitor according to claim 2, wherein said actual heat transfer module (60) comprises a plurality of difference units (63), a plurality of multiplication units (64, 65), a plurality of division units (66) and a natural logarithm function unit (61), all of said units being connected together to calculate the actual heat transfer coefficient for the heat exchanger according to the function:

$$U_{act} = \frac{C_p m_w (T_{hot} - T_{cold})}{A(T_{hot} - T_{cold})} \left(\ln \frac{T_{hot} - T_3}{T_{cold} - T_3} \right)$$

where:

C_p	is the specific heat of the heat exchange medium,
m_w	is the mass flow rate of the heat exchange medium,
T_{hot}	is the input temperature of the medium,
T_{cold}	is the output temperature of the medium,
A	is the heat exchange surface area, and
T_3	is the heat exchanger temperature on the opposite side of the heat exchange surface.

FIG. 1


19
MASS FLOW
LOGIC UNIT
FT 2
18
CONDENSER
COOLING UNIT
M
11
16
M
COMPR.
14
17
S
FT 2
20
FOULING
MONITOR
LOGIC
(FIG. 2)
(FF)
FOULING
FACTOR
T'HOT
T'COLD
10
TCOLD
THOT
EVAP.
12
TT 2
TT 1
FT 1
LT 1
TT 3

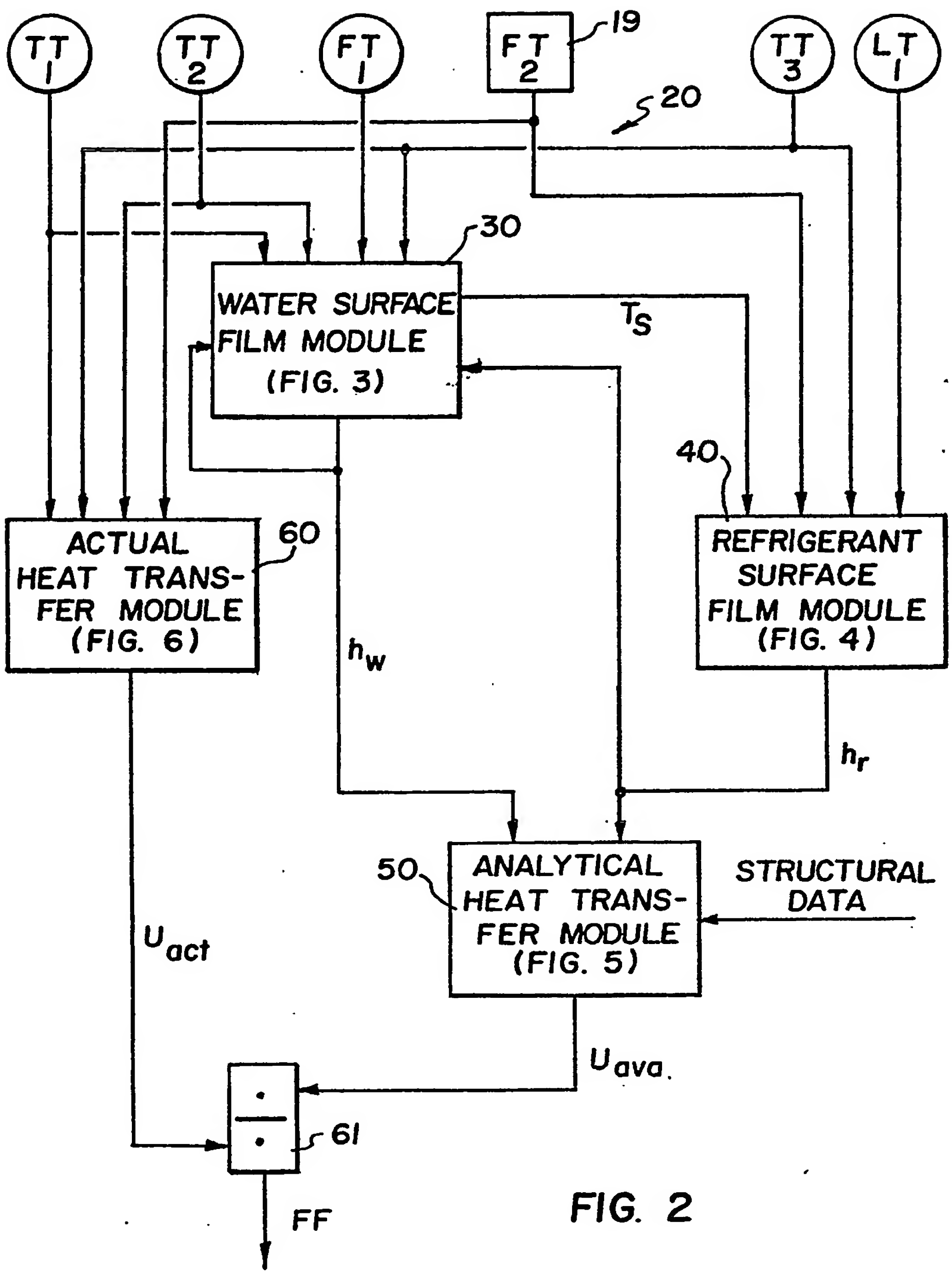
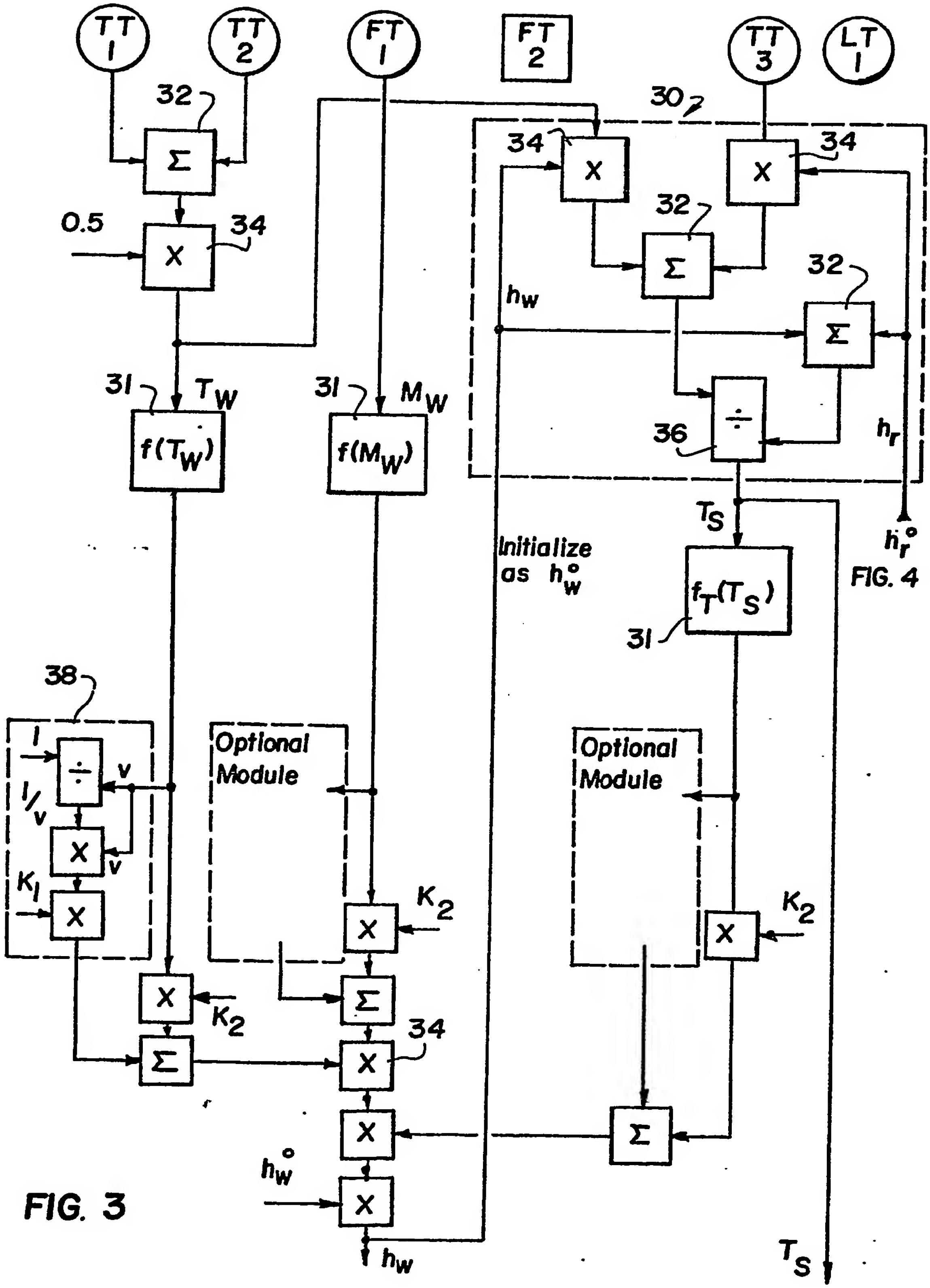

TT 1
TT 2
FT 1
FT 2
19
TT 3
LT 1
20
30
WATER SURFACE FILM MODULE (FIG. 3)
T_S
40
REFRIGERANT SURFACE FILM MODULE (FIG. 4)
ACTUAL HEAT TRANSFER MODULE (FIG. 6)
60
h_w
h_r
50
ANALYTICAL HEAT TRANSFER MODULE (FIG. 5)
STRUCTURAL DATA
U_{act}
$U_{ava.}$
61
FF

FIG. 2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h_r
T_S
h_r^o
Initialize as h_w^o
$f_T(T_S)$
38
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v
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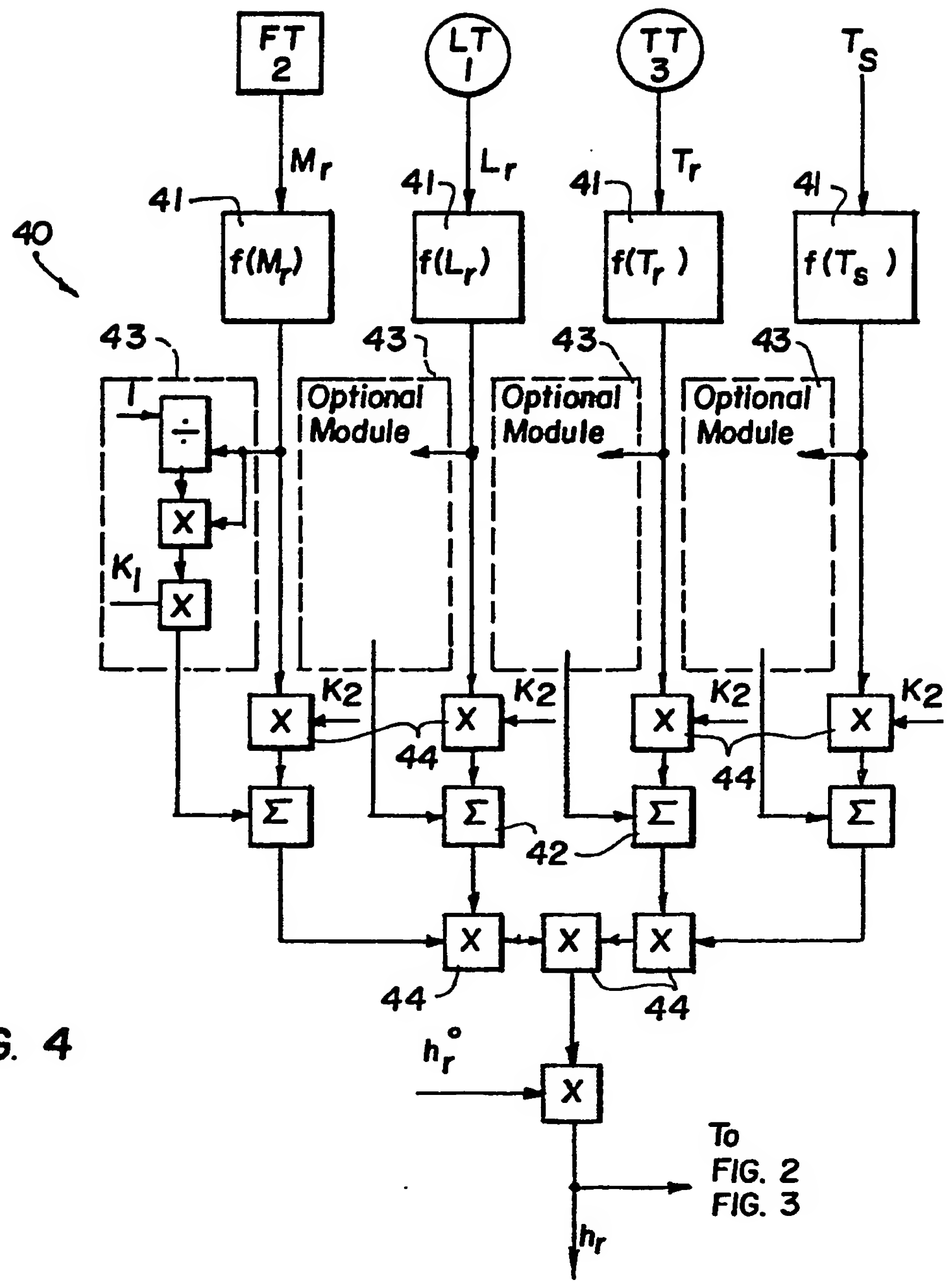
K_2
Optional Module
Optional Module
h_w^o
h_w
T_S

FIG. 4

FIG. 3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43
I
÷
X
K_1
X
Optional Module
Optional Module
Optional Module
K2
K2
K2
K2
X
X
X
X
44
44
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Σ
Σ
Σ
42
X
X
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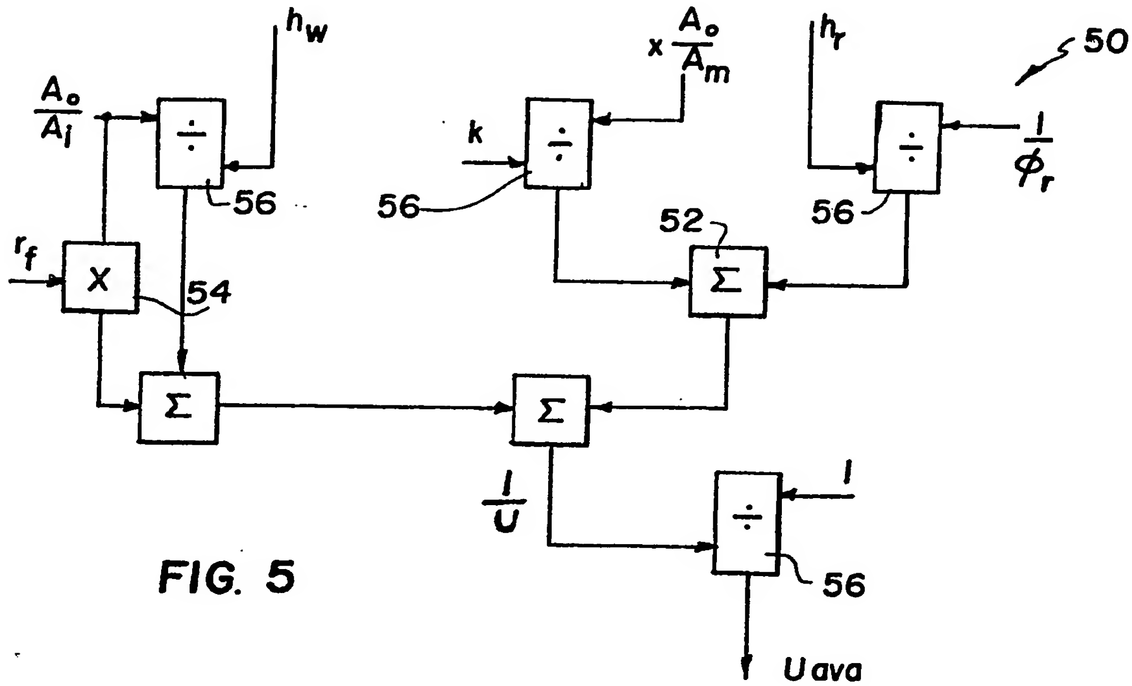
44
44
h_r^o
X
To FIG. 2 FIG. 3
h_r

FIG. 4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54
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$x\frac{A_o}{A_m}$
k
÷
56
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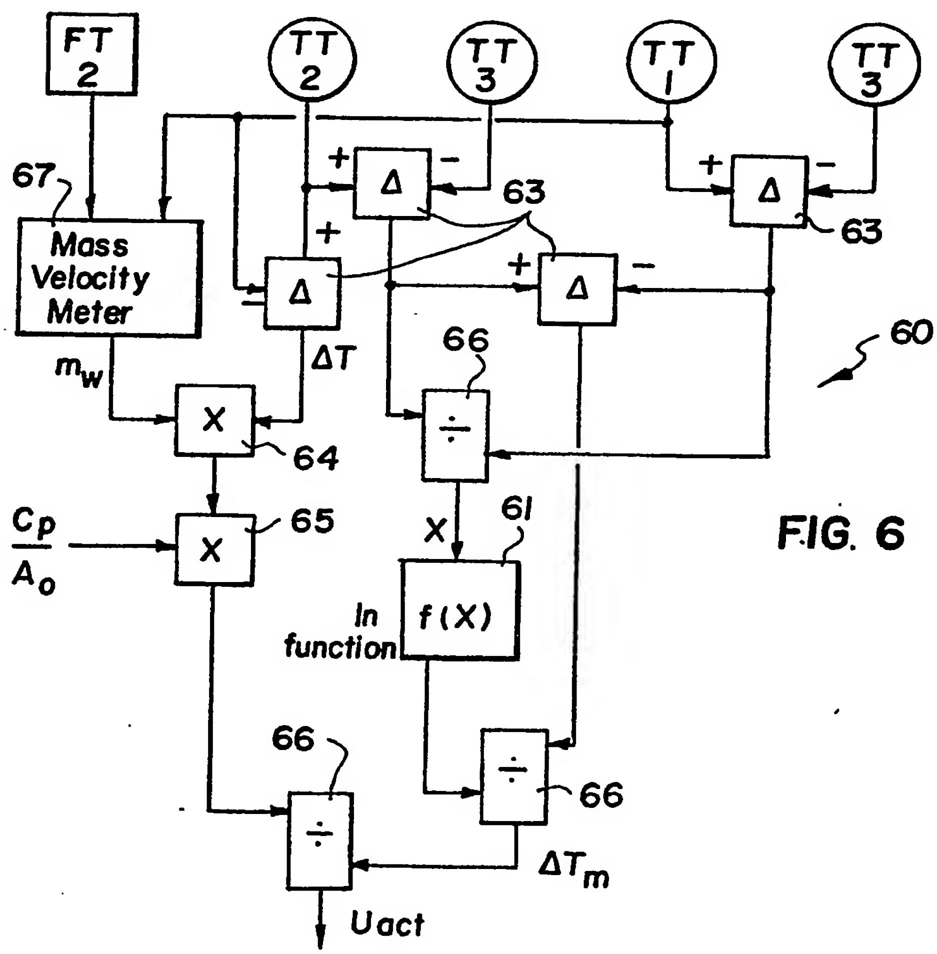
Uava

FIG. 5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61
ln function
f(X)
60
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÷
66
ΔT_m
Uact

FIG. 6